

MRI-PHY/P981169
nucl-th/9811064

Matter effects on η and η' mesons

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Abstract

We show how the nuclear medium affects the masses of the η and η' mesons. The change should be easily detectable for dense matter and/or strong $\eta(\eta')N\bar{N}$ coupling. We also find that the $\eta - \eta'$ mixing angle is less in magnitude in the nuclear matter than in vacuum.

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A proper way of understanding the nature of the nuclear force is to study the interaction between nucleons and low-lying mesons. The nucleon mass gets shifted from its vacuum value of ~ 938 MeV due to the radiative corrections generated by the scalar mesons inside the medium. This correction has been evaluated in different theoretical frameworks, *e.g.*, the mean-field (MF) model and the relativistic Hartree (RH) model. In turn, the meson masses are affected by the nucleon propagators, modified due to the density-dependent contributions.

The change of masses for the vector mesons ρ and ω and their mixing due to the nuclear medium have been widely investigated in the literature[1]. One of the advantages for such a treatment for vector mesons is the fairly well-established (but model-dependent) couplings between the meson and a nucleon-antinucleon pair [2], which leads to a more or less robust prediction. Among the pseudoscalar mesons, the coupling of pion to the nucleons can be evaluated from the Goldberger-Treiman relation, and is bound to be derivative in nature since π is a Goldstone boson. Such a pseudovector coupling necessarily generates a small shift for the pion mass. On the contrary, little is known about the $\eta N\bar{N}$ and $\eta' N\bar{N}$ couplings. A fit to the one-boson exchange potential (OBEP) generates a value of $\alpha_\eta (= g_{\eta N\bar{N}}^2/4\pi)$ in the range of 3 to 7 [3], whereas flavour SU(3) relations and chiral perturbation theory predict this quantity to be below 1 [4]. The value of $\alpha_{\eta'}$ is inferred to be between 0.25 and 0.75 [5] from the pp scattering data. However, since η and η' are much heavier, these couplings need not be completely pseudovector, and there can be sizeable pseudoscalar components.

As we will show, such couplings introduce significant mass shifts for the η and η' mesons as well as a mixing between them, analogous to the matter-induced $\rho - \omega$ mixing discussed in [6]. This result is valid even if the meson-nucleon coupling is an effective one generated through a vertex loop [3]. These shifts should be easily detectable in future hadronic colliders through the relatively clean channels $\eta \rightarrow 2\gamma$, $\eta \rightarrow \ell^+\ell^-\gamma$, $\eta' \rightarrow \rho^0\gamma$, $\eta' \rightarrow \omega\gamma$, $\eta' \rightarrow 2\gamma$ with a subsequent proper identification of ρ^0 and ω . The branching ratios for the above channels in vacuum are 0.39, $5 \times 10^{-3}(3 \times 10^{-4})$, 0.30, 0.03 and 0.021 respectively (for the second channel, the first number is for $e^+e^-\gamma$ and the second one is for $\mu^+\mu^-\gamma$) [7]. We will also show the behaviour of the matter-induced mixing angle as a function of nuclear density. The two-photon decay modes of both η and η' are affected by the meson masses as well as the mixing angle and can in principle provide a clear testing ground for such density-dependent effects.

The relevant part of the nuclear Lagrangian is [3]

$$\mathcal{L}_{\eta N\bar{N}} = -ig_{\eta N\bar{N}}\bar{N}\gamma_5 N\eta \quad (1)$$

where we have neglected the pseudovector coupling, which has a small contribution on mass shift and mixing. A similar Lagrangian can be written for η' . All the unknown factors, including those arising from an effective coupling generated by vertex loops, are dumped into $g_{\eta N\bar{N}}$.

The nucleon propagator in nuclear matter may be expressed as

$$G(k) = G_F(k) + G_D(k) \quad (2)$$

where

$$G_F(k) = (\not{k} + M^*) \left[\frac{1}{k^2 - M^{*2} + i\epsilon} \right] \quad (3)$$

and

$$G_D(k) = (\not{k} + M^*) \left[\frac{i\pi}{E^*(k)} \delta(k_0 - E^*(k)) \theta(k_F - |\mathbf{k}|) \right] \quad (4)$$

with $E^*(|\mathbf{k}|) = \sqrt{|\mathbf{k}|^2 + M^{*2}}$, M^* being the effective mass of the nucleon in the medium. Since the main contribution to M^* arises from the isospin blind σ meson, $M_n^* = M_p^*$. The term $G_D(k)$ arises from Pauli blocking and describes the modifications of the propagator at zero temperature by deleting the on-shell propagation of the nucleon in nuclear matter with momenta below the Fermi momentum k_F . Since we will focus only on symmetric nuclear matter, $k_F^p = k_F^n$; at this limit, π^0 does not mix with either η or η' .

The radiative correction to the pseudoscalar mass can be written as

$$-i\Pi(q^2) = \int \frac{d^4k}{(2\pi)^4} (-1) \text{Tr}[\gamma_5 iG(k+q) \gamma_5 iG(k)] \quad (5)$$

where the negative sign is due to the fermion loop. Writing $G = G_F + G_D$, we see that the trace consists of four terms. Among them, the combination $G_D(k+q)G_D(k)$ does not contribute in the region in which we are interested, and the effect of the free part $G_F(k+q)G_F(k)$, being only a running of the coupling constant $g_{\eta N\bar{N}} \rightarrow g_{\eta N\bar{N}}(q^2)$, can be neglected since q^2 itself is quite small in the long-wavelength collective-mode region [8]. However, if one wants to see the collective mode over the entire region of \mathbf{q} and q_0 , the free part cannot be neglected; one needs a suitable subtraction procedure and the implementation of a momentum-dependent coupling. One can show that pseudovector couplings have a small contribution in the long-wavelength limit.

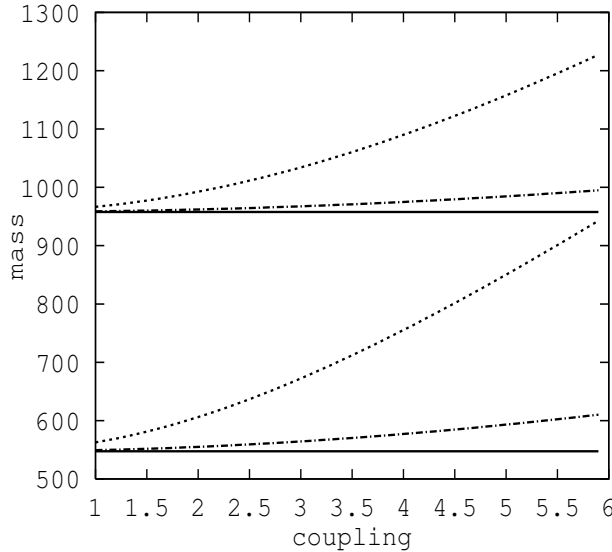


Figure 1: Variation of η and η' masses with coupling $g_{\eta N\bar{N}}$ ($g_{\eta' N\bar{N}}$). The upper set is for η' while the lower one is for η . The dot-dashed lines are for ρ/ρ_0 (nuclear density ratio) equal to 1 whereas the short-dashed lines are for $\rho/\rho_0 = 6$. The horizontal solid lines indicate the vacuum masses.

As we have seen, η and η' do not mix with π^0 in the symmetric limit. The polarization can be written as a 2×2 matrix which is of the form

$$\begin{pmatrix} 1 - \frac{\Pi_{\eta\eta}}{q_0^2 - m_\eta^2} & \frac{\Pi_{\eta\eta'}}{q_0^2 - m_\eta^2} \\ \frac{\Pi_{\eta'\eta}}{q_0^2 - m_{\eta'}^2} & 1 - \frac{\Pi_{\eta'\eta'}}{q_0^2 - m_{\eta'}^2} \end{pmatrix} \quad (6)$$

$(\Pi_{\eta\eta'} = \Pi_{\eta'\eta})$. The shifted masses are obtained from the solution of the following equation:

$$(q_0^2 - m_\eta^2 - \Pi_{\eta\eta})(q_0^2 - m_{\eta'}^2 - \Pi_{\eta'\eta'}) - (\Pi_{\eta\eta'})^2 = 0. \quad (7)$$

Since the bare masses of η and η' are quite far apart, we neglect their decay widths. The matter-induced mixing angle θ_{mix} is given by

$$\theta_{mix} = \frac{1}{2} \tan^{-1} \left[\frac{2\Pi_{\eta\eta'}}{(m_\eta^{*2} - m_{\eta'}^{*2})} \right], \quad (8)$$

where $m_\eta^{*2} = m_\eta^2 + \Pi_{\eta\eta}$, and same for η' .

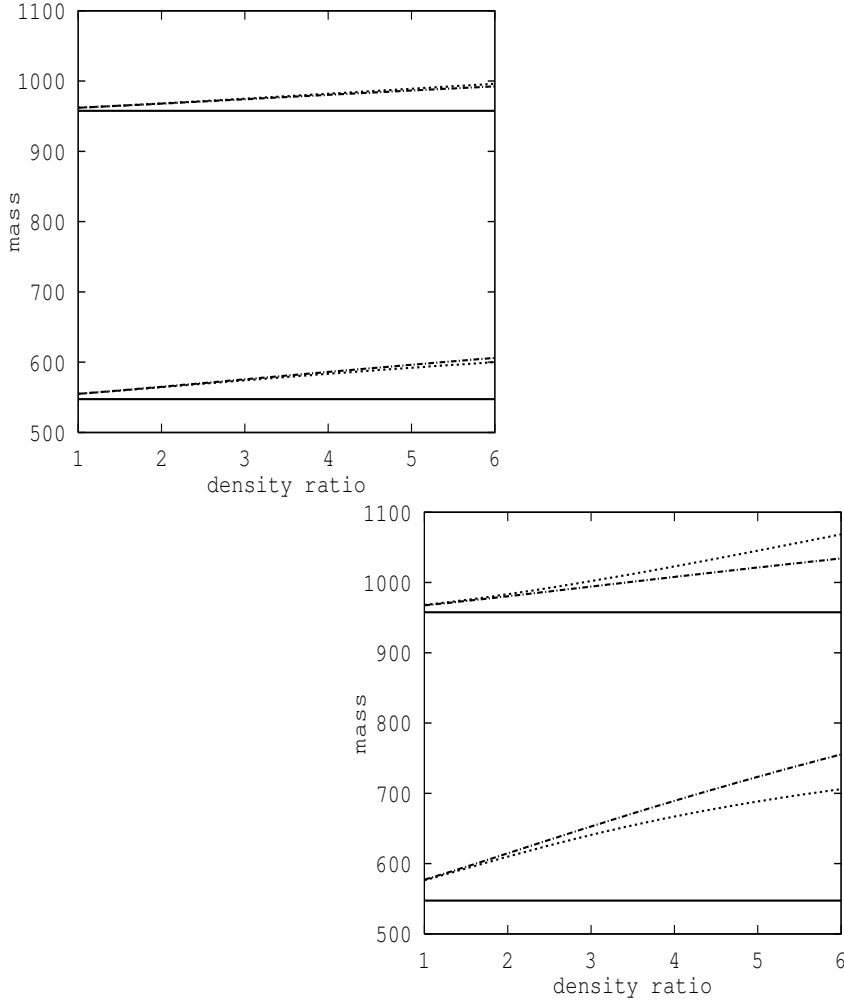


Figure 2: Variation of η and η' masses with nuclear density. In both the figures, the upper set is for η' and the lower set is for η . The dot-dashed lines are without mixing while the short-dashed lines are with mixing. The horizontal solid lines indicate the vacuum masses. In the left-hand figure, $g_{\eta N\bar{N}} = g_{\eta' N\bar{N}} = 2$ while in the right-hand figure, $g_{\eta N\bar{N}} = 4$, $g_{\eta' N\bar{N}} = 3$.

Now let us discuss our results. In figure 1, we show the variation of meson masses with couplings $g_{\eta N\bar{N}}$ or $g_{\eta' N\bar{N}}$ for two different densities. We note that the change is significant in the strong coupling limit even for ordinary nuclear matter, and for not-so-strong couplings in dense matter. This is without taking the mixing into account; as we will see, mixing enhances

the η' mass and reduces the η mass. This behaviour is shown clearly in figures 2a and 2b; in figure 2a, the effect is shown for both $g_{\eta N\bar{N}}$ and $g_{\eta' N\bar{N}}$ equal to 2, whereas in figure 2b, $g_{\eta N\bar{N}} = 4$ and $g_{\eta' N\bar{N}} = 3$. The range of $g_{\eta' N\bar{N}}$ is more or less fixed from ref. [5], but $g_{\eta N\bar{N}}$ can be larger (however, the one-loop Dyson equation approach has no meaning for a very strong coupling).

Assuming both couplings to be positive, we show the plot of the mixing angle θ_{mix} with nuclear density in figure 3. This angle always turns out to be negative, as the denominator in

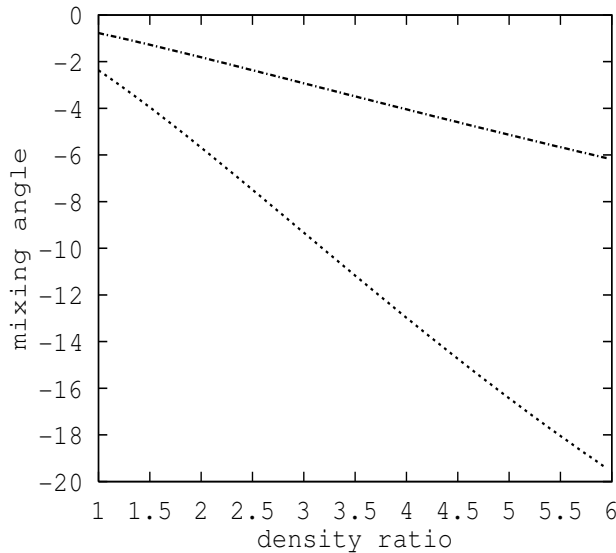


Figure 3: Variation of $\eta - \eta'$ mixing angle with nuclear density ratio. The dot-dashed line is for $g_{\eta N\bar{N}} = g_{\eta' N\bar{N}} = 2$ and the short-dashed line is for $g_{\eta N\bar{N}} = 4$, $g_{\eta' N\bar{N}} = 3$.

eq. 8 contains a negative quantity, viz., $m_{\eta}^{*2} - m_{\eta'}^{*2}$. Thus, the vacuum mixing angle of η and η' , inferred to be $(-21.3 \pm 1.5)^\circ$ from the $\gamma\gamma$ decay mode [9, 10], gets reduced in nuclear matter. In other words, the medium tries to rotate η and η' back to the gauge basis of η_1 and η_8 . This is a prediction which should be testable in future colliders. The two-photon decay width depends on $m_{\eta/\eta'}^3$ and the mixing angle [10]. Since both these quantities change in the medium, the decay width is affected in a nontrivial way. We show the two-photon decay width in figure 4. As can be seen, the effect is not very prominent for η at weak coupling, but for η' , it should be easily detectable. To observe the effect for η , one needs a strong $g_{\eta N\bar{N}}$ coupling as well as sufficiently dense nuclear matter.

As we have said earlier, there are other clean channels to see the matter effects on η and η' , with ρ or ω being detected in their leptonic channels.

To conclude, we have shown how η and η' masses change in a nuclear matter, where we have assumed the presence of pseudoscalar couplings for both these mesons. The change is quite significant and should be easily detectable for large nuclear densities and/or strong meson-nucleon coupling. The mixing angle is found to be negative compared to the vacuum mixing angle, but smaller in magnitude than the latter. The $\eta(\eta') \rightarrow \gamma\gamma$ modes can shed more light on this issue.

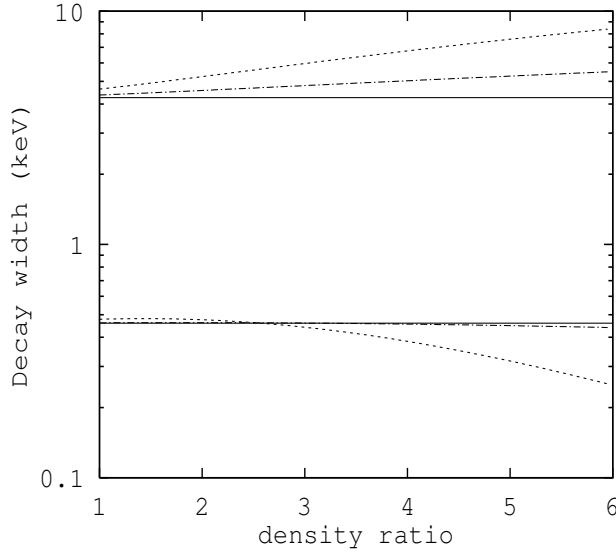


Figure 4: Variation of two-photon decay widths of η and η' with nuclear density. The upper set is for η' and the lower set is for η . The dot-dashed lines are for $g_{\eta N\bar{N}} = g_{\eta' N\bar{N}} = 2$ and the short-dashed lines are for $g_{\eta N\bar{N}} = 4$, $g_{\eta' N\bar{N}} = 3$. The horizontal solid lines denote their decay widths in vacuum.

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